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3-D GRMHD and GRPIC SIMULATIONS OF DISK-JET COUPLING AND EMISSION

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We investigate jet formation in black-hole systems using 3-D General Relativistic Particle-In-Cell (GRPIC) and 3-D GRMHD simulations. GRPIC simulations, which allow charge separations in a collisionless plasma, do not need to invoke the frozen condition as in GRMHD simulations. 3-D GRPIC simulations show that jets are launched from Kerr black holes as in 3-D GRMHD simulations, but jet formation in the two cases may not be identical. Comparative study of black hole systems with GRPIC and GRMHD simulations with the inclusion of radiate transfer will further clarify the mechanisms that drive the evolution of disk-jet systems.

1. GRPIC numerical simulations and initial results

So far the black hole system has been investigated only by GRMHD simulations, which ignore various important kinetic effects, in particular, charge separation due to different motions of electrons and positrons/ions in a magnetic field.[1–4] We investigated magnetic coupling in disk-jet system with proper treatment of kinetic physics, using our general relativistic particle-in-cell (GRPIC) code (for details, see Watson et al. 2006[5]). Our objective is to identify the essential micro-physics for jet formation.

The underlying physics of the particle motion is the contravariant form of the Newton-Lorentz equation. This form provides the equation for the acceleration of the particle. The acceleration is a function of the spacetime curvature defined by the metric and the Lorentz force due to the electromagnetic field. The local field

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is described by the Maxwell field tensor. The components of the tensor are calculated using the contravariant general relativistic form of Maxwell's equations. Using these three equations, the particles are moved and the fields and currents are calculated self-consistently. The individual kinematics of the system governs the evolution of the simulation. The algorithm uses the relativistic PIC method.[6] The particle motion is calculated by integrating the equation of motion using a fourth order Runge-Kutta. Similarly to the RPIC, the electric and magnetic field components of Maxwell's field tensor are offset in space and time.

We present results of our 3-D simulations of jet formation using general relativistic plasma particle dynamics in Kerr metric (angular momentum $a = J/J_{\max} = 0.9$). The initial setting of the simulation is as follow: a background plasma (8 electron-positron pairs/cell), a free falling corona, and a Keplerian disk as that in GRMHD Simulations.[1–4] The black hole is located at the origin. The particle number of the corona is 1/100 of the disk. The Keplerian disk is located at $r > r_{\mathrm{D}} \equiv 3r_{\mathrm{S}}\,|\cos\theta| < \delta$, where $\delta = 1/8$, r_{D} is the disk radius and $r_{\mathrm{S}} \equiv 2GM/c^2$ is the Schwarzschild radius. In this region the particle number is 100 times that of the corona. The orbital velocity of the particles in the disk is $v_\phi = v_{\mathrm{K}} \equiv c\sqrt{r_{\mathrm{S}}/(2r)}$, where v_{K} is the Keplerian velocity, $r = \sqrt{-a^2/2 + R^2/2 + \frac{1}{2}\sqrt{(a^2 - R^2)^2 + 4a^2z^2}}$, and $R^2 = x^2 + y^2 + z^2$.[7] There are no disk particles initially at $r < r_{\mathrm{D}}$. The initial magnetic field is taken to be uniform in the z direction. The magnitude of the field is 10^4 gauss. This field component is the contravariant z component of the field.

Figure 1 shows GRPIC simulations of co-rotating jets launched from the disk along the $y-z$ plane at $x = 0$. The angular momentum of particles shearing towards the black hole is transferred to the jet, causing it to spiral. The particles are ejected away from the black hole, which leads to formation of bipolar jets. Figure 1 also shows a 3-D view of particle velocities. The most remarkable phenomenon is that the jet is actually composed of streams of particles with different velocities. Such streams are kinematically unstable, easily giving rise to non-linear and collective behaviors, which leads to bunching, clumping and shock formation. Also noticeable is the development of spiral structure (color). We note that the jet structure depends upon the plasma particle species assumed in the simulation. At this time there is a need to quantify the parameters required for jet formation. Our study of particle ejection has demonstrated that jet material consists of particle pairs, i.e. not restricted to baryons as assumed in many theoretical models. The particles in the jet maintain some angular momentum and continue to spiral around the central axis.

The simulations do not show significant magnetic field deformation. This may be a consequence of the number and the strength of particles prescribed in the simulation. More particles may cause a stronger disk magnetic field and hence a stronger electric field, due to the particles falling towards the horizon. Another possible explanation for the lack of significant field deformation is that the frozen-in condition is relaxed. In GRMHD simulations, as the frozen-in condition $\vec{E} = -\vec{v}\times\vec{B}$ is used, the magnetic fields are dragged by the fluid motion. The relative significance

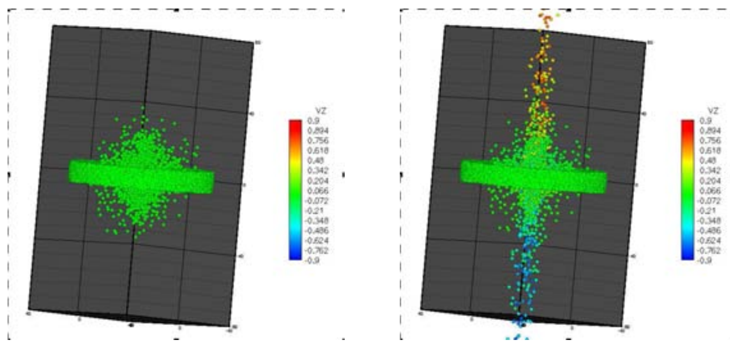

Fig. 1. The 3D views of disk and corona particles are shown at $t/\tau_{\rm S} = 0$ and 1134 ($\tau_{\rm S} = r_{\rm S}/c$). Particle pairs are moving through the jet at different velocities. The jet has a structure which forms spirals around the z (central) axis.

of each of these effects is crucial for proper understanding of jet formation and needs to be quantified.

The inclusion of radiation transfer (Fuerst et al.2006[8]) is essential to make observational predictions and hence to verify the findings in the GRPIC and GRMHD simulations.

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References

1. K.-I. Nishikawa, G. Richardson, S. Koide, K. Shibata, T. Kudoh, P. Hardee, and G. J. Fishman, *ApJ* **625**, 60 (2005)
2. Y. Mizuno, K.-I. Nishikawa, S. Koide, P. Hardee, and G. J. Fishman, *ApJS*, submitted, (2006a) (astro-ph/0609004)
3. Y. Mizuno, K.-I. Nishikawa, S. Koide, P. Hardee, and G. J. Fishman, *ApJL*, submitted, (2006b) (astro-ph/0609344)
4. Y. Mizuno, K.-I. Nishikawa, S. Koide, P. Hardee, and G. J. Fishman, in this proceeding, (2006c)
5. M. Watson, K.-I. Nishikawa, and Y. Mizuno, *ApJ*, in preparation, (2006)
6. K.-I. Nishikawa, P. Hardee, C. B. Hededal, and G. J. Fishman, *ApJ* **642**, 1267 (2006)
7. S. C. Bell, *Compt. in Phys.* **9** 281 (1995)
8. S. Fuerst, Y. Mizuno, K.-I. Nishikawa, and K, Wu, *ApJL*, in preparation (2006)